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Abstract

In this paper we describe results from the Hoe Creek No. 3 underground coal gasification test. The experiment employed a drilled channel between process wells spaced 130' apart. The drilled channel was enlarged by reverse combustion prior to forward gasification. The first week of forward gasification was carried out using air injection, during which 250 tons of coal were consumed yielding an average dry product gas heating value of 114 Btu/scf. Following this phase, steam and oxygen were injected (generally a 50-50 mixture) for 47 days, during which 3945 tons of coal were consumed at an average rate of 84 tons of coal per day and an average dry gas heating value of 217 Btu/scf. The average gas composition during the steam oxygen phase was 37% H_2, 5% CH_4, 11% CO, and 44% CO_2. Gas recorvery was approximately 82% during the test, and the average thermochemical efficiency was near 65%.

Introduction

In-situ coal gasification is an old idea which has become more attractive as the alternatives have become less attractive. The basic concept involves partial oxidation of a coal deposit underground and subsequent recovery of a combustible gas at the surface. Means for in-situ coal gasification were developed in the USSR in the 1930's, but discovery of large oil and natural gas resources caused a decline in the use of in-situ gasification by the USSR. Development of these techniques also started in the United States in the 1950's, but low cost oil and natural gas precluded our use of in-situ coal gasification at that time.

The progressive depletion of oil and natural gas resources has made use of coal resources much more attractive. However, large increases in coal production using conventional methods are difficult because of new emphasis on human health and well being in the case of deep mining and because of environmental impact concerns in the case of strip mining. In-situ coal gasification obtains energy from coal deposits without the underground labor associated with deep mining and without the massive surface disruption associated with strip mining.

The basic coal gasification process is simple in concept, consisting of three steps: 1) the coal is heated which drives off water and then volatiles to form char (as in destructive distillation), 2) the char reacts with hot steam to form CO + H_2, and 3) finally the remaining char reacts with O_2. The char/O_2 reaction provides the heat to drive all the other reactions, which are endothermic. The char/H_2O reaction produces CO and H_2. The pyrolysis reaction also produces CO and H_2 as well as a wide range of hydrocarbon products.

Although simple in concept it is still necessary to demonstrate the technical feasibility of the process by performing actual field experiments. Since 1973, seventeen underground coal gasification (UCG) field test have been conducted in the U.S. A brief summary of these experiments is given in Table I. As can be seen, these tests typically run 30 or more consecutive days at coal consumption rates of 30-100 tons per day. Thus the UCG tests, though simple, are comparable in output with aboveground coal gasification pilot plants. Both low and medium Btu product gas has been obtained, by air and steam/oxygen injection, respectively.

Due to these repeated demonstrations of technical feasibility, underground coal gasification is recognized as one of the most promising methods to produce clean fuels from coal. Successful UCG technology would quadruple the U.S. proven reserves of coal: from 0.4 trillion to 1.8 trillion tons. The resource would be adequate for hundreds of years' production. The projected product costs of \$0.90-1.00/gallon for gasoline and \$3.50-4.00/10^6 Btu for synthetic natural gas (refinery costs) are competitive with conventional sources. If successful, commercial production could being in ten years or less.[1]

The objective of this report is to describe results of the Hoe Creek No.3 experiment, which was the first long-term UCG steam/oxygen underground coal gasification test ever conducted. The experiment was carried out by the Lawrence Livermore Laboratory in the Powder River Basin near Gillette, Wyoming, under the sponsorship of the U.S. Department of Energy and the Gas Research Institute.

Goals

The major design goals of the Hoe Creek No. 3 experiment were to:[2]

1. Carry out forward gasification with a known, reliable link at the bottom of the coal seam.
2. Determine steam/oxygen gasification efficiencies at coal consumption rates up to 100 tons/day.
3. Gasify at commercial process well spacings (100-200 ft.)
4. Determine burn zone configuration.
5. Minimize gas losses and water influx.
6. Determine water quality and subsidence effects.

These objectives were accomplished in an experiment that lasted 57 days and consumed 4200 tons of coal. During the 47 days of oxygen injection the average heating value of the gas produced was 217 Btu/scf (193 kj/mol).[3]

Table 1 United States UCG field tests.

Air injection unless otherwise noted

Test #	Year	Duration (days)	Gas quality (Btu/scf)	Dry gas production (10^6 scf/day)	Gas* losses (%)	Tons gasified (tons)
A. Sponsored by U.S. Government						
• LETC, Hanna, Wyoming						
Hanna 1	1973-74	180	126	1.6	~0	4000
Hanna 2-1	1975	38	152	1.7	~0	1260
Hanna 2-2	1975	25	175	8.5	~0	2520
Hanna 2-3	1976	38	138	12	~0	4200
Hanna 3	1977	38	130	10	~0	2850
Hanna 4	1977-79	24	133	8.3	~0	1500
• LLL						
Hoe Creek 1	1976	11	102	1.2	7	129
Hoe Creek 2	1977	58	108	3.3	20	2480
Hoe Creek 3 (oxygen only)	1979	47	217	3.4	19	3950
• METC, Pricetown, W VA						
Pricetown	1979	12	127	3.4	~0	350
• GULF/TRW						
Rawlins, Wyoming	1979	30	150	3.8	~0	1020
		5	250 (oxygen)	3.4	~0	200
B. Sponsored by private industry						
• Texas Utilities Services, Inc.						
Fairfield, Texas	1976	26	126	–	–	–
Tennessee Colony, Texas	1978-79	197	81	2.5	–	–
		10	230 (oxygen)	1.0	~0	212
• ARCO						
Reno Junction	1978	60	200	4.7	–	3600
• Texas A&M University (with industrial consortium)						
College Station, Texas	1977	1	35-114	0.3	–	2
Bastrop County, Texas	1979	21	85	1.4	–	–

*~0 implies less than 5% gas losses

We directionally drilled a link between process wells prior to gasification at Hoe Creek 3. This was to avoid problems at Hoe Creek 2 in which reverse combustion was used to create the link. Although reverse combustion linking has been used successfully in the past, the link path is not well controlled and at Hoe Creek 2 a path across the top of the coal seam resulted. Directional drilling allowed us to define the initial process geometry by placing a link at a known location near the bottom of the Felix 2 coal seam.

Figure 1 shows the relationship of the process wells and the directionally drilled channel DD-1 to the underground lithology. This channel was drilled during July of 1978, using a 2 3/8" diameter Dyna-Drill mud motor to drill a 3" diameter hold. The drilling started at 30° to the surface and was deviated (maximum rate of 5° per 100 feet) so that the borehole was essentially horizontal in the area of interest. Five process wells were drilled to intersect the horizontal well (DD1).

The basic experimental plan was to gasify the coal between wells A and B by oxgyen/steam injection in A and with gas production mainly from well B with occasional production from well C. One week of air gasification was planned at the beginning of the experiment to allow a direct comparison with the results of Hoe Creek 2. Wells P1 and P3 were designed as pump wells for dewatering the channel and burn zone as long as possible and well P1 was also designated as an auxilliary injection well.

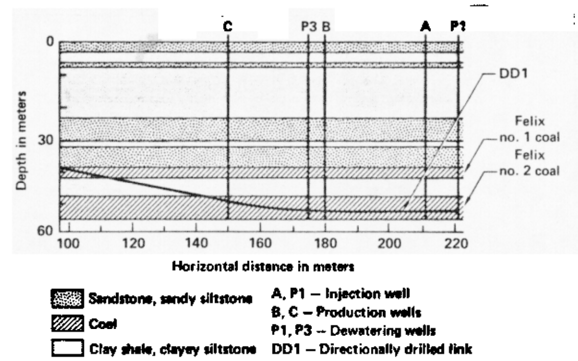

Fig. 1 Hoe Creek 3 process wells and channel.

Wells B and P3 intersected DD-1 when drilled and wells A and P1 were connected by using a water jet drill loaned to us by the U.S. Bureau of Mines.* We were unable to link well C with DD-1 before the burn and after an unsuccessful attempt to link by forward combustion during the gasification phase, the well was abandoned

*Arranged by George Savanick, Twin Cities Mining Research Center, Minn.

The three main process wells P1, A and B were designed to maintain injection and production locations near the bottom of the coal seam as long as possible (Figure 2). The design utilized a 13" - 3/8 casing packed with high temperature cement, with 10" - 3/4 inner liner. The well internals, oxygen lance, gas lift pipe and dewaterling line were protected inside the inner liner with water cooling in the annulus between the inner and outer casing. The 3 inch oxygen lance, shown in Fig. 2 was included only in wells P1 and A. Its purpose was to allow oxygen to be injected near the bottom of the coal seam and mixed with steam that had been injected through the casing liner. The lower 60 ft of the A-well lance was made of Monel, with the remainder copper. The P1 lance was copper. The pump well P-1 was designed to be a back-up injection well to replace well A, if necessary.

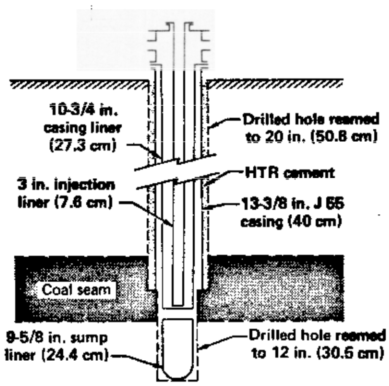

Fig. 2 Typical process well design.

Instrumentation

A plan view of the well array is shown in Fig. 3. Since the A well was designated as the main injection well, the thermal instrumentation was grouped around this well and in the area between the injection and production wells. There were fifteen thermocouple wells, each well containing an average of 14 junctions spaced at intervals throughout the coal seams and overburden. Additional thermocouples were fastened to the outside of all of the process well casings. The thermocouple wells were designed to monitor the progress of the burn down DD-1 and also to define the boundaries of the burn cavity during the last two thirds of the experiment.

Sandia Laboratories, Albuquerque provided three items for use in the experiment. A COMUX data logger[4] that collected all of the data from all instrumentation and sent the data to the computer on command. An inverted thermocouple assembly,[5] designed to avoid burnout, transmitted downhole thermocouple measurements to a reciever located beyond the gasification region. The third item was an Electrical Remote Monitoring (ERM)[6] network designed to monitor the progress of the burn front.

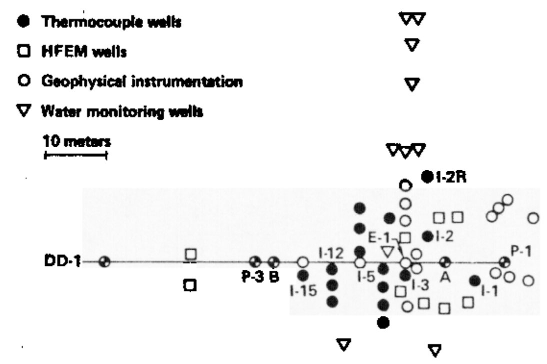

Fig. 3 Hoe Creek 3 plan view of well array.

Eight HFEM[7] wells were used to monitor burn cavity growth during the early stages of the experiment. This technique utilizes the change in transmission of an RF signal caused by heating and burning the coal. Radio transmitters and receivers are placed in the wells and the signals are recorded on the surface.

Seventeen geophysical instrumentation[8] installations of various kinds were used to monitor underground motion. These included extensometers, piezometers, shear strips and deflectometers. Fifteen water wells were emplaced to allow monitoring of the groundwater before, during and after the burn for environmental information.

The product gas was analyzed by a process gas chromatograph and a time-of-flight mass spectrometer. Injection and production flow rates were measured with orifice flow stations. All of the data were collected by the COMUX scanner and input to the computer. The computer processed and stored the data via a data base management system. This processed data was available both in graphical and tabular form to the process operators to aid in the control of the experiment.

The Experiment History

Following plant construction and checkout, initial hydrology and air flow testing indicated that wells P1, A, B, and P3 were well connected to the drilled hole DD-1, while well C was not connected. Based on pressure drop measurements, DD-1 was estimated to have an equivalent pipe diameter between 3/4 and 1 1/4 inches.

Ignition of the coal occurred on August 14, 1979 (day 226), when an electrical ignitor, covered with broken coal at the bottom of well B was turned on. Air injection was into well A and gas production was from well B.

The 57 day gasification period[9] for Hoe Creek 3 is best described by dividing it into five different phases. We will discuss each in turn.

Reverse burn phase (day 226.5 - day 229.3)

Since the drilled channel was too small to give the required low pressure drop at the design flow rates, it was decided to enlarge the hole by reverse combustion. Laboratory tests[10] had shown that reverse combustion would not propagate in a drilled hole in coal as wet as the Felix coal (30% water). However, we had been successful in using reverse combustion in the natural fractures of the coal during Hoe Creek 2. Therefore we decided to try using air for Hoe Creek 3 to see if there was any effect of scale size in the actual in-situ process.

After one day of operation, it was clear that the burn remained at the B well and was not propagating up DD-1.

We then added propane to the air stream, keeping the concentration below the lean flammability limit. Although this did increase the rate of burning and the downhole temperature, the reverse burn still did not propagate.

Finally, oxygen was added to enrich the air stream to about 35% oxygen which was a few percent above the minimum oxygen, concentration indicated by the laboratory experiments. Seventeen hours later the reverse burn front reached the injection well. From both pressure drop and coal consumption data the resulting hole produced was estimated to be about 6 inches in diameter.

Air Gasification (day 229.3 - day 236.4)

After the reverse burn hole enlargement was completed, the scheduled seven day air gasification was started from well A toward well B. The goal of this phase of the experiment was to provide a direct comparison of air gasification with a drilled link (Hoe Creek 3) to air gasification with a reverse combustion link (Hoe Creek 2).[11]

The injection flow was increased in small steps from 4 mol/s to 56 mol/s (200 to 2800 scfm) over a three day period. There was no effect on the produced gas heating value from changes in the flow rate. Particulate production, however, did increase considerably as the flow rate increased. After one day of operation at the peak injection rate of 56 mol/s, the injection flow was reduced to 40 mol/s (2000 scfm) and finally to 30 mol/s (1500 scfm) to control particulate emissions. Reducing the flow rate was a reasonably successful solution to the particulate emission problem although some particulates were produced at the lowest flow rates tried.

On the fourth day of forward gasification, the HFEM diagnostic system reported that the burn zone had reached the top of the Felix 2 coal seam near the injection well. Within a few hours the steam content of the gas increased dramatically and the gas heating value dropped from 113 Btu/scf to 90 Btu/scf. Production flow was still through DD-1 to well B. The degradation in heating value was caused by roof collapse in the vicinity of well A, which increased heat loss from, and water intrusion into, the gasification zone.

A comparison of the performance of Hoe Creek 2 and Hoe Creek 3 during similar time periods is shown in Table 2. It would seem reasonable to assume that the linking method had little or no effect on the initial phase of the burn process.

Table 2 Initial air gasification - Hoe Creek II and III.

	Hoe Creek II	Hoe Creek III
Period (days)	10	7
Coal consumed (m^3)	207	183
Inj rate (mol/s)	32	36
Higher HV (kJ/mol)	101	101

First P1 Oxygen Injection Phase (day 236.5 - 243.7)

Towards the end of the scheduled air burn we attempted to establish flow communication through the oxygen injection lance in the A-well. The lance was found to be plugged, probably by slag. Therefore the reserve injection system in well P1 was used for the oxygen/steam injection which started on August 24, 1979 (day 236). Within one half hour the pressure drop between wells A and P1 dropped to less than 1 psi and within two hours the heating value rose to 260 Btu/scf.

The start-up oxygen/steam ratio was 20% O_2 and 80% steam. This was changed gradually over the next two days to 20 mol/s (1000 scfm) oxygen and 20 mol/s steam in an effort to maintain a high heating value. Since changing the ratio did not seem to produce any lasting effect, the 1 to 1 ratio was adopted as the operating standard for most of the rest of the experiment.

Three days after the start of oxygen injection, on day 239, the extensometer E1 (near DD-1) indicated collapse of the roof and large quantities of steam were emitted from the flare.

Two days later the thermocouples at I-5 (near DD-1) indicated burn temperature had reached the roof of the seam at that point. Over the next week high temperature indications at the top of the seam were noted at all thermocouple stations along the DD-1 channel.

The interpreation of the thermocouple, geophysical and HFEM data is that the drilled channel, DD-1, grew much faster vertically than horizontally during this period and, that in a little over two weeks of gasification, the drilled hole had become a V-shaped slot extending from the original height to the top of the coal seam. Subsequently the burn zone began to widen and from this time to the end of the experiment the operation was characterized by a steady gas composition that seemed to be independent of almost all operating parameters.

A-well Oxygen Injection Phase (day 243.8 - day 253.2)

On day 241 pressure tests indicated that the blockage of the A-well oxygen lance was gone. Since most of the HFEM diagnostic wells were clustered around A well, we returned the injection point to A well for the next ten days. Near the end of the period it appeared from the HFEM data that the burn zone had shifted almost entirely into the upper coal seam, Felix 1. Postburn examination of the A well oxygen lance showed that it had been broken off above Felix 1 coal seam by a massive collapse of the overburden. The collapse had filled in below the break so that most of the injected flow was into Felix 1.

Second P1 Oxygen Injection Phase (day 253.8 - day 283.5)

Although thermocouples in P1 indicated that the oxygen lance in P1 was also broken or melted above Felix 1, the casing and liner seemed to be intact further down. Therefore oxygen/steam injection was switched back to well P1. Over the next few days both the HFEM data and thermocouple data indicated increased activity in Felix 2 and a decrease in Felix 1.

This operating mode was continued until the end of the experiment. The burn continued to involve both coal seams and steadily grew wider. The burn appeared to move along the top of the seam, moving outward and down very slowly. The inverted thermocouple in well I-2 showed this most clearly.

On day 283, October 10, 1979 the experiment was ended. A few tenths of a percent of oxygen began to appear in the product gas and in a few hours the production well temperatures rapidly increased. In spite of water cooling rates exceeding 10 gpm, the production well casing temperature exceeded 700C. The injection flow was shut off and in a few hours the well cooled off and the cooling water shutoff.

Final Burn Geometry

A total of 2816 m^3 of coal were consumed during the Hoe Creek 3 test. This number includes corrections for the estimated 18% gas loss during the experiment. The correction to the coal consumed number is made by assuming the lost gas had the same composition as product gas. In the absence of any correction for gas losses the total coal consumed was 2316 m^3. This latter number would only be valid if all the lost gas had the same composition as the injection gas. We consider this unlikely, and as a result used the gas loss corrected number in conjunction with thermal data to infer the burn boundaries.

The thermal data on burn boundary location are limited, especially in the Felix 2 coal seam and in the vicinity of the main injection well P1. As a result the following description of burn boundary locations is tentative. Coring will be needed to derive final burn boundary estimates with a reasonable degree of confidence.

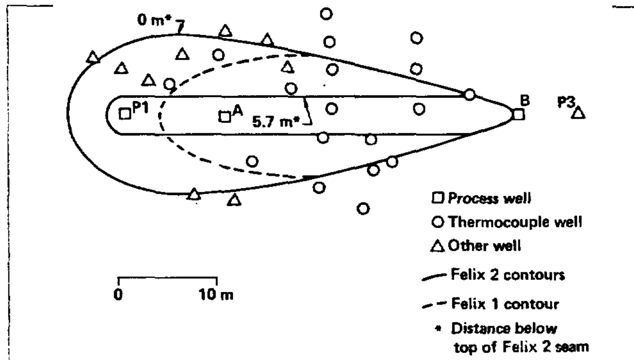

Fig. 4 Final burn boundaries in the Felix 1 and 2 coal seams.

Figure 4 shows the proposed burn boundaries at the end of the experiment. The dotted line represents the extent of burning in the 3 m thick Felix 1 seam, estimated to be 970 m^3, while the solid lines represent the burn boundaries in the 7.7 m thick Felix 2 seam, estimated to be 1830 m^3.

We have assumed that in the Felix 2 seam the unburned boundary can be represented by an outward sloping volume. Lines representing the 0 and 5.7 m levels of burning (measured from the top of the seam) are shown. It is assumed that the central region running from wells P1 to B is flat and about 3.5 meters wide at a depth of 5.7 m into the seam. There is no thermal evidence to justify this assumption. The 5.7 m depth was chosen to coincide with the original location of DD1, while the width was chosen to yield the appropriate coal consumption. The slope was derived solely from the information provided by the inverted thermocouple in I2, which indicated a maximum burn depth of 2.5 - 3 m. The outer boundary was drawn to be consistent with the lack of thermal responses from I4, I7, I10, and I13 and a total coal consumption number of 1830 m^3 for Felix 2.

The dotted line in Fig. 4 representing the extent of burn in Felix 1 was drawn to be consistent with thermal data. The line represents the extent of a burn which would have taken 100% of the Felix 1 coal if it had vertical sides. If we assume that the sides were sloped the outer burn boundary could be extended. The only direction for a large extension would be towards P1 since the boundaries nearer the production well (B) are constrained by thermal data. The shape of the boundary drawn was strongly influenced by our knowledge of the location of the surface subsidence which occurred after the end of the experiment. The main subsidence crater is located between A and B wells with a center approximately 6-8 m from A well. We could not justify this crater location based on coal consumption from Felix 2 and therefore felt compelled to skew the Felix 1 burn boundary toward the B well, with the inference that the coal removal from this upper seam would have influenced the location of the subsidence more than that of the lower Felix 2 seam. This skewed burn is also supported by the strong indications of a burn in Felix 1 during the injection into A period.

Summary of Results

The product gas composition and the higher heating value of the gas for the time periods discussed are shown in Figs. 5 and 6 respectively.

During the first two weeks of forward combustion, the burn zone rose twice to the top of the coal seam: once at well A with air injection, and again at P-1 with oxygen-steam injection. In addition, the drilled channel grew faster vertically than horizontally as the coal dried out, and it eventually became a slot extending up to the roof of the seam.

Comparing the arrival times of burn temperature at the top of the coal along DD1 with those near the injection well indicates that the product gas was still flowing through the main body of the coal after the cavity had reached the roof and the heating valve had begun to decline.

Roof collapse partially filled the slot with rubble. The burn cavity moved rapidly along this path. Two weeks after the start of forward burn, the thermocouple at the top of Felix 2 in well I-12, 10 m from well B reached 1000°C; five days later the same temperature was recorded at the top of I-15, 5 m from well B.

However, from this time until the end of the experiment 34 days later, the burn velocity along the channel slowed markedly and the cavity began to expand laterally. At this time, the injection point was returned to P-1 from well A.

During this lateral growth period, the fluctuations in the gas heating value grew smaller and the heating value itself became more constant, although it was 5 to 10% lower than the average value recorded during the previous time period.

A summary of the pertinent data for the various phases of the experiment is given in Tables 3-5.

Table 6 shows a comparison of the Hoe Creek 2 and Hoe Creek 3 experiments in terms of energy fraction and some economic related factors. The similarities are obvious and strongly indicate that at least at Hoe Creek the site characteristics are more important than the details of the process.

The Hoe Creek 3 experiment showed that we could operate with oxygen-steam injection in a routine manner for a long time. The directionally drilled linking channel was completed and enlarged by reverse combustion successfully. We demonstrated that the product gas quality deteriorated when the burn zone reached the roof of the coal seam even though the gas flow was still through the directional link channel.

After about three weeks of forward burn, the system became quite stable and the heating value and gas composition remained nearly constant until the end of the experiment.

We were unable to maintain the injection point at the bottom of the coal seam in this experiment. Both the oxygen lances in wells A and P1 were broken or melted above the coal seam. Judging from the results of Hoe Creek 2, the loss of the bottom injection point probably contributed significantly toward the lower than expected heating value produced. It is doubtful, however, whether even a consistent bottom injection point would have completely overcome the problems caused by the weak, wet roof materials.

About two weeks after the burn ended a subsidence crater appeared on the surface 10 meters from well A towards well B. This crater enlarged over the next few weeks until it reached dimensions of approximately 10 meters by 20 meters and two meters deep. We are continuing to monitor the slow changes in the subsidence pattern at regular intervals.

A series of core holes will be drilled into the burned zone to further diagnose the extent of the burn and the collapse region.

The type of overburden, weak claystones and sandstones, found at the Hoe Creek site is certainly less favorable to the in-situ process than one would desire. We are searching for a new site with a stronger, drier overburden that should be more favorable.

Conclusions

- The drilled channel, DD1, directed the flow of product gas through the coal seam during the early stages of the experiment. Despite this fact early time product quality problems were encountered as a result of interactions with wet overburden material near the injection well.
- The drilled channel evolved over the course of the first 12 days of the experiment into a slot which eventually channeled flow at or above the top of the coal seam. We see no evidence in the data that this influenced the course of the gasification.
- The injection well completions were not successful in maintaining the injection point at the bottom of the seam. We feel this may have adversely effected the process.
- Continued interaction with wet overburden material hurt the overall performance of the process.
- The use of oxygen/steam as the primary injected reactant caused no unexpected operational problems.
- The overall performance of the Hoe Creek 2 and 3 experiments was similar.
- The geologic setting at Hoe Creek is not optimal for UCG. We speculate that a drier and tougher coal and overburden would yield superior results.

Acknowledgments

Although there were far too many people to list separately who made significant contributions to this experiment, we want to proffer special thanks to our engineering staff and our chemistry personnel and to the very able personnel from Sandia Laboratories.

We also want to thank our support contractor Stearns-Roger, for their able assistance.

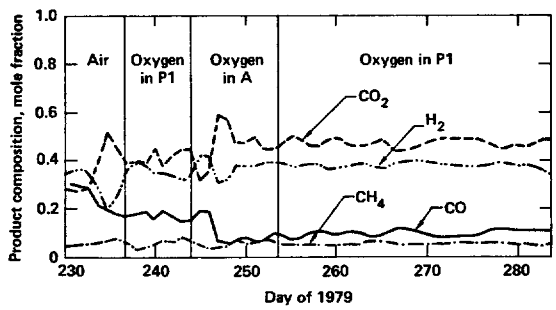

Fig. 5 Nitrogen free dry product gas composition for the entire gasification phase.

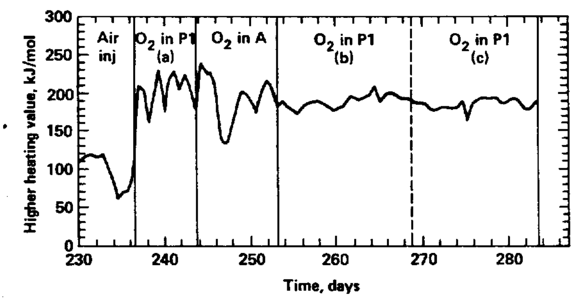

Fig. 6 Gas heating value for Hoe Creek 3.

Table 3 Operational data summary for Hoe Creek 3.

Time period day of 1979	Injection flow rate (mol/s)	Injection flow rate (scfm)	Injected oxygen mole fraction	Production dry flow rate (mol/s)	Production dry flow rate (scfm)	System pressure (kPa)	System pressure (psia)	Total produced dry gas (10^6 mol)	Coal gasified (m^3)	Coal gasified (tons)
Reverse burn with oxygen										
228.6 – 229.3	5.0	252	0.31	8.6	433	335	48.7	0.52	3.57	5.32
Forward burn with air										
229.5 – 236.4	35.5	1782	0.21	53.4	2680	287	41.6	31.8	168	250
Oxygen burn with injection in P1 (a)										
236.5 – 243.7	39.3	1974	0.45	54.6	2740	322	46.7	34.0	389	580
Oxygen burn with injection in A										
243.8 – 253.2	38.0	1907	0.49	40.9	2054	350	50.8	33.2	358	533
Oxygen burn with injection in P1 (b)										
253.5 – 268.5	42.4	2131	0.47	48.6	2439	288	41.8	63.0	699	1041
Oxygen burn with injection in P1 (c)										
268.5 – 283.5	41.8	2101	0.48	47.1	2365	263	38.1	61.0	677	1001
Total oxygen burn										
236.5 – 283.5	40.8	2051	0.48	47.5	2383	297	43.0	192.8	2137	3185

All mol units are gram moles
Dry refers here to moisture and tar free
Coal gasified is not corrected for gas losses
Coal total FB gas loss cor ~4200 tons

Table 4 Product composition and material balance data summary for Hoe Creek 3.

Time period day of 1979	Dry-tar-free product gas average mole fractions N_2	H_2	CH_4	CO	CO_2	Product gas H_2O/dry gas ratio*	Reaction stoichiometry O_2/C	H_2O/C	Gas recovery (%)	Water influx (mol/s)
Reverse burn with oxygen										
228.6 – 229.3	0.41	0.20	0.016	0.17	0.19	0.17	0.48	0.19	102	–3.3
Forward burn with air										
229.5 – 236.4	0.56	0.14	0.024	0.11	0.14	0.52	0.52	0.24	109	18.5
Oxygen burn with injection in P1 (a)										
236.5 – 243.7	0.016	0.35	0.052	0.18	0.39	1.34	0.50	0.31	99	46.5
Oxygen burn with injection in A										
243.8 – 253.2	0.029	0.37	0.051	0.12	0.42	1.12	0.51	0.38	67	30.0
Oxygen burn with injection in P1 (b)										
253.5 – 268.5	0.010	0.37	0.051	0.095	0.46	1.08	0.55	0.35	82	31.7
Oxygen burn with injection in P1 (c)										
268.5 – 283.5	0.015	0.37	0.049	0.095	0.46	1.29	0.56	0.34	80	40.7
Total oxygen burn										
236.5 – 283.5	0.018	0.37	0.051	0.113	0.44	1.20	0.53	0.34	81	36.5

*Ratio is a mole ratio

Table 5 Energy data summary for Hoe Creek 3.

Time period day of 1979	Product gas heat of combustion* kJ/mol	Btu/SCF	Energy distribution: Combustible gas %	Net steam %	Gas sens heat %	Insitu loss %	Product HC† per mole of O_2 kJ/mol
Reverse burn with oxygen							
228.6 – 229.3	124	141	67	4	2	27	676
Forward burn with air							
229.5 – 236.4	101	114	72	16	9	3	663
Oxygen burn with injection in P1 (a)							
236.5 – 243.7	208	236	69	13	5	13	649
Oxygen burn with injection in A							
243.8 – 253.2	197	224	69	12	7	13	650
Oxygen burn with injection in P1 (b)							
253.5 – 268.5	189	214	64	10	8	18	559
Oxygen burn with injection in P1 (c)							
268.5 – 283.5	184	208	63	14	9	15	532
Total oxygen burn							
236.5 – 283.5	192	217	65	12	8	15	580

*Dry, tar-free

†Dry, tar-free H C. Use recovery number to obtain kJ/mole for actual O_2 injected.

Note: energy as combustible gas includes contributions from tar

Table 6 Overall comparison of Hoe Creek 2 and 3.

	II	III
Energy fraction		
Combustible prod.	0.68	0.66
Steam	0.10	0.13
Prod. sensible heat	0.06	0.08
Insitu loss	0.16	0.14
Gas recovery	80%	83%
Coal consumed	1662 m^3 (2480 tons)	2810 m^3 (4190 tons)
Based on produced gas		
kJ/O_2	612	586
O_2/C	0.50	0.53

References

1. U.S. Department of Energy, "Underground Coal Conversion, Program Description,": DOE/ET-0100, (1979).

2. R.W. Hill, D.R. Stephens, S. Thompson, R. Aiman, J. Cena, C.B. Thorsness, H.C. Ganow, R. Stone and J.E. Clarkson and L. Bartel and George Davidson, (Sandia Laboratories) "LLL 1979 Field Program," presented to Fifth UCC Symp. June 1979, Alexandria Va., (preprint UCRL-82428).

3. W.R. Aiman, R.J. Cena, R.W. Hill, C.B. Thorsness, D.R. Stephens, "Highlight of the LLL Hoe Creek No. 3 Underground Coal Gasification Experiment," to be published in In-Situ (preprint UCRL-83768) (1980).

4. Unit designed and named by Sandia Laboratories.

5. T.W.H. Caffey and D.E. Barnes, "A Buried Telemetry System for Temperature Measurements," Proc. of 6th UCC (to be published).

6. L.C. Bentel, "Analysis of the Electrical Potential Data for Hanna IV Underground Coal Gasification Test," Proc. of 4th UCC, Steamboat Springs, Co., July 1978, Sandia Laboratories, SAND 78-0941.

7. D.T. Davis, R.J. Lytle, and E.F. Laine, "Use of High-Frequency Electromagnetic Waves for Mapping an In-Situ Coal Gasification Burn Front." UCRL 81016 (1978).

8. H.C. Ganow, R.C. Greenlaw and R.T. Langland, "Geotechnical Instrumentation Applied to In-Situ Coal Gasification Induced Subsidence," Proc. of 4th UCC Steamboat Springs, Co., July 1978, Sandia Laboratories, SAND 78-0941.

9. LLL In-Situ Coal Gasification Project Quarterly Progress Report July through September 1979. UCRL 50026-79-3.

10. W.R. Aiman, R.W. Lyckowski, C.B. Thorsness and R.J. Cena, "Reverse Combustion in Horizontally Bored Coal Channel," 5th UCC Alexandria, Va., (preprint, UCRL-82505).

11. C.B. Thorsness, R.J. Cena, W.R. Aiman, R.W. Hill and D.R. Stephen, "Hoe Creek No. 2: Underground Coal Gasification Experiments with Air and Oxygen/Steam Injection Periods," preprint UCRL 80921 Soc. of Pet. Eng. of AIME, Houston (1978).

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